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The detection of abandoned mineshafts by railway track bed using transmitted seismic waves using broadside shot gathers

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THE DETECTION OF ABANDONED MINESHAFTS BY RAILWAY TRACK BED USING TRANSMITTED SEISMIC WAVES USING BROADSIDE SHOT GATHERS

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Abstract

The practical challenges of mineshaft detection under railway embankments are discussed, together with typical mineshaft properties over the centuries. The paper focuses on the broadside shot seismic transmission method to detect abandoned mineshafts, with the potential to be used in the vicinity of embankments. A numerical model was developed, using a new type of absorbing boundary condition, which is referred to as the Recursive Integration Perfectly Matched Layer. From a series of simulations using this model, a series of practical outcomes were identified regarding the feasibility of the broadside seismic transmission method. These include the layout of the geophones, the frequency of the shot source together with ways of improving the signal to noise ratio. The results from a field trial in East Lothian, Scotland are compared with the output from the numerical model and good agreement was identified.

1. Introduction

Buried mineshafts that were abandoned over a century ago pose a present day threat to the stability of the ground above. For obvious safety reasons these mineshafts need to be accommodated for. To remediate a mineshaft its exact location has to be known. Unfortunately documentation on mine workings before 1872, the year when it became compulsory to keep detailed plans, are unreliable and sometimes non-existent.

It is estimated that there are still 30,000 out of 100,000 workings in the United Kingdom which are unrecorded [Culshaw and Waltham, 1987]. The issue is of course an international problem, with abandoned mine workings widespread across the USA, for example. The detection of abandoned mine workings, whilst not easy, has been well documented (Jiang, Karunaratna Jones, 2004).

In the UK context, mine shafts can be found widely spread throughout the country, but the vast majority are located between Edinburgh and Glasgow, the Midlands, Wales and around Newcastle (Figure 1). It is reasonable to assume that numerous shafts are present in the vicinity of both highways and railways. These workings date from the prehistoric times to late 19th century, but the majority were excavated during the last three centuries.

This is especially true for concealed mineshafts in urban areas and near infrastructure such as highways and railways. In order to diminish the risk, it is essential that the abandoned shafts are located and stabilised.

This paper will make reference to the challenges of detecting abandoned mine shafts beneath embankments.

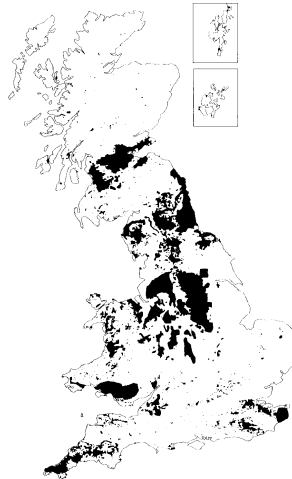


Fig. 1. Mining map of the United Kingdom [Woodland and Statham, 1992]

2. Mineshafts

2.1. Development of mineshafts

The early mining operations in the United Kingdom consisted of quarrying the materials from exposed outcrops and from shallow seams [Burke, 1988]. Often adits were driven from the outcrops into the seam permitting the extraction of the ore or coal. Another common method used in the early days of mining is by means of bell pits. Bell pits were mainly used for flint mining and mining iron stones; although some bell pits have been found in shallow coal fields. A bell pit is a single vertical shaft sunk to the bottom of the seam which is worked to a limited extent around the shaft till there were signs of the roof collapsing. Generally, bell pits were no more than 12m deep, although bell pits of up to 30m deep were constructed. The diameter of mined area around the central shaft spanned from 8m to a maximum 20m. Bell pits were used until the 17th century [Littlejohn, 1979].

In the 15th century new techniques to extract the seam came into existence such as room-and-pillar mining and shortwall mining and longwall mining. In the beginning these mine workings were accessed by one single mineshaft. Although sometimes a connection with another colliery was established allowing air ventilation. During the 17th and 18th centuries it became more common to have two or more mineshafts. The separation between these mineshafts can be merely 3m apart to being opposite ends of the mine workings. For deeper mine workings it was still common to use one single mineshaft, but due to frequent accidents it became compulsorily in 1852 to have at least two mineshafts per mine working.

The invention of steam-driven pumps in 1712 improved the draining of the mine workings and greater depths could easily be achieved. At the end of the 18th century mineshafts of 250m deep were constructed. The trend of increasing maximum depths continued until modern times. Figure 2 illustrates the general trend of maximum depths of mineshafts for the last four centuries. Similar to maximum depth of the mineshaft, the width of mineshafts increased over the last centuries. During the 1600s the average diameter of a mineshaft was merely 1m. The average diameter rose to 2m around 1750, although mineshafts with 1m diameter were still constructed. The diameters of mineshafts around the 1900s were between 2.5 and 7.5m. An overview of the development of the diameter of the mineshafts over the last centuries can be found in Figure 2.

With increasing mineshaft depths and diameters, it became necessary to support the mineshaft to prevent it from collapsing. Mineshaft linings were used since the 17th century. In the beginning wooden linings were used and two centuries later it became

common practice to use bricks for lining. During the sinking of the mineshaft, wooden and sometimes iron frames were to support the mineshaft initially and thereafter brickwork was constructed within the frame. The use of metal linings became common through the 19th and 20th century. At the close of the 20th century concrete lining was introduced.

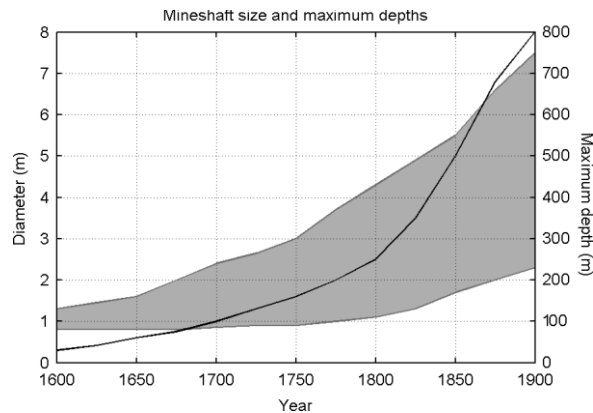


Fig. 2. The development of the diameter (grey area) and the maximum depth (black line) of the last centuries (after Dean, 1967)

2.2. Closure of mineshaft

After closure of the mine working, the mineshaft had to be sealed for safety reasons. There were various methods to secure an abandoned mineshaft and today abandoned mineshafts can be encountered in various conditions. The most common conditions are represented in Figure 3. The chosen practice to secure a mineshaft depends mainly on the size of the mineshaft. Deep mineshafts were very unlikely to be completely backfilled and the most common practice was to backfill the abandoned mineshafts partially. This method consisted of building a scaffold just below ground level or near the bed rock. Sometimes the upper part of the lining was removed and the scaffold was built on the remaining lining. In 1871 the Mines Inspectorate recommended the use of large wooden logs for the scaffolding. These logs were fixed together and laid across the mineshaft.

However regardless of the recommendation, it was more common to dump mine tubs, trees or even colliery steam engines into the mineshaft, which formed an obstruction. Hereafter the mineshaft was backfilled till ground level. The material used for backfilling consisted of almost anything that was available at the site. Generally it consisted of colliery and building waste such as wood, ropes, ashes from the engines, some lining material, and remnants of rock through which the mineshaft was sunk. The backfilling might be mixed with superficial deposits.

Abandoned mineshafts that were not partially or completely backfilled were secured by either fencing the area off or by capping. There was little consistency in the methods of capping. Although these mineshafts are dangerous, they do not constitute any direct danger to the public since their locations are generally well known.

2.3. Collapse of the mineshaft

The primary cause of the collapse of a partially backfilled mineshaft is the failure of the platform or obstruction that supports backfill [Dean, 1967]. There are various reasons why the platform or obstruction may give way:

- In the situation where an obstruction (mineshaft F), constructed by dumping discarded tubs, trees, it is obvious that the construction is inherently unstable.

- In the case where there was a proper platform built from wood inside the mineshaft (mineshfts C-E), it is still possible that it will collapse due to deterioration of the wood and the backfilling migrates to the bottom.
- In the situation where the platform was built on the rim of the lining (mineshaft E), it is possible that the lining itself gives way. A possible cause is that the wooden frame between soil or rock and the brick lining has disintegrated, leaving the brick lining unsupported.
- The backfilling has a porous nature or consist of fine material (mineshaft C-E). When subjected to water, the backfilling becomes plastic and can be forced down the mineshaft like a paste.
- In the case where the platform is built on the rock head (mineshaft D), failure of the rock head can occur due to the load of the platform on the brittle bedrock [Littlejohn, 1979].

Note that although completely backfilled mineshafts (mineshaft F) do not collapse, they can cause subsidence at the surface due to settlement of the backfilling. Furthermore claims of old mineshafts that were completely backfilled might not be true - unknowingly or knowingly - and the unstable situation of mineshaft E might be closer to the truth.

3. Detection of burried mineshafts

Suitable procedures to investigate the location of a mineshaft were outlined by the Department of Environment and summarized by McCann et al. [1987]. A flow chart representation of the summary can be found in Figure 4. Basically the investigation procedure consists of three phases. The first phase is a comprehensive desk study to gather all potential information about the site and the mineshaft. The desk study is followed by a field reconnaissance which includes geophysical or geochemical surveys. Sometimes the desk studies yield enough information on the exact location of the mineshaft and the field reconnaissance phase is bypassed. In order to confirm the location conclusively field investigations are required. Usually these field investigations consist of drilling boreholes, but can also consist of trenching and other excavation techniques [Bell, 1975].

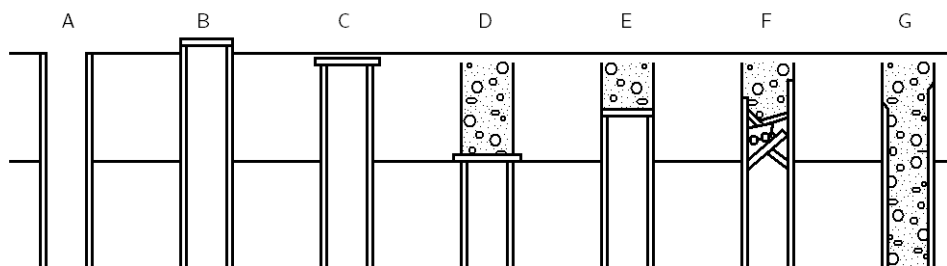


Fig. 3. The various states of mineshafts encountered at present day: A - completely open, B - capped with the platform above the surface, C - capped with platform on the or just below the surface, D - backfilled with platform on the bedrock head, E - backfilled with platform on the rim of the lining, F - backfilled with material clogging the mineshaft and G - completely backfilled

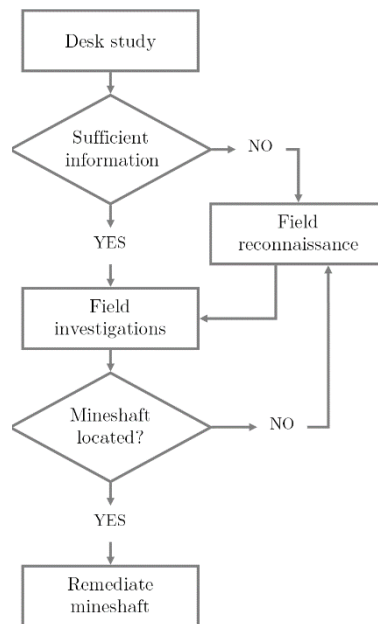


Fig. 4. Procedures regarding the investigations and remediation of mineshafts

4. Field reconnaissance

The purpose of the field reconnaissance is to identify anomalies which might be related to the presence of the mineshaft. Anomalies that manifest on the surface can be identified by visual inspections. Visual inspection is a cheap and fast survey method. Anomalies that are located in the subsurface can be identified by either a geochemical or a geophysical survey. The choice of the geochemical or geophysical survey technique depends on its ability to quantify the anomaly produced by the mineshaft. The anomaly can be produced by the void, backfilling, lining of the mineshaft or by a combination of the various elements. Additionally the de-stressed bedrock around the mineshaft can cause anomalies. Whether the anomaly can be observed in the data obtained by the chosen survey technique depends on the physical dimensions, shape and depth, the physical or chemical properties of the mineshaft and the surrounding material; this is in relation to the penetration depth, resolution and signal-to-noise ratio of the selected technique [McCann et al., 1987]. Hence knowledge about properties of the mineshaft and its surrounding is pivotal in the process of selecting the survey method that most likely will resolve the mineshaft.

4.1. Reconnaissance near embankments

The presence of a highway or railway embankment presents a challenge to reconnaissance techniques. Visual inspections and geochemical surveys are deemed to be ineffective to delineate mineshafts beneath embankments. Many geophysical techniques might prove ineffective due to the lack of penetration depth and the attenuation caused by the presence of metal. Furthermore many techniques would require possession of the road or track, which is highly undesirable.

5. Seismic methods

In this paper we propose an unconventional seismic method to delineate mineshafts by mapping the time delay of refracted compressional waves. Seismic methods are not often used in near-surface geophysics and especially not in the delineation of small voids. One reason is that the wave lengths of the seismic waves are typically an order of one or two larger than the target and hence it is difficult to resolve small targets by conventional seismic methods.

A second reason is that seismic methods are generally more expensive than popular methods such as electrical resistivity tomography and ground penetrating radar. Furthermore seismic surveys require a comparably larger crew and furthermore seismic surveys are time consuming. By using broadside survey lines rather than survey lines where the sources is in line with the receivers, large areas can be surveyed quickly. This makes the proposed method very efficient in time and costs. Unlike for example reflection seismics, this method delineates anomalies in the surface by mapping certain trace attributes e.g. travel time rather than using the whole trace to produce an image of the subsurface. This results in a higher resolvability and small targets such as a mineshaft can be resolved. This method does not require possession of the highway or railway track. Therefore this method is particularly attractive for the delineation of mineshafts which are present in the proximity of major transport lines, such that the traffic is not affected by the survey.

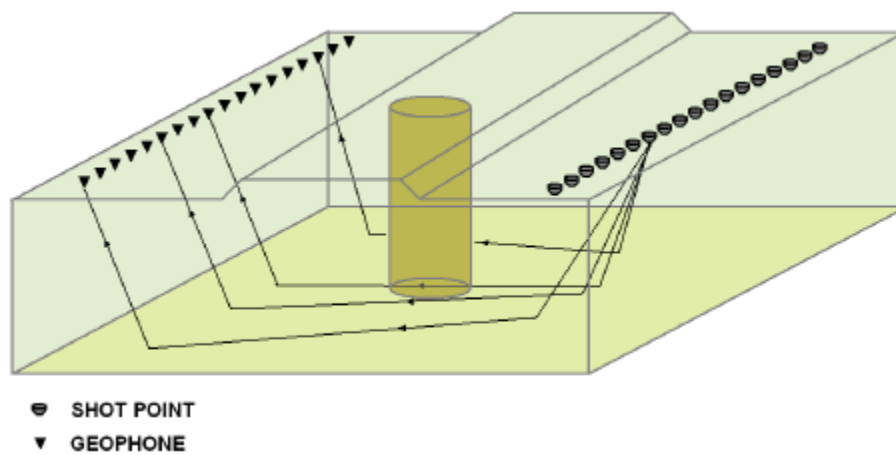


Fig. 5. Refracted waves travelling along the ray paths going through the mineshaft are affected by the mineshaft whereas waves travelling away from the mineshaft are unaffected

6. Transmission method

The method discussed in this paper is based on the transmission method [Dresen et al., 1975, Dresen, 1977, Dresen and Hsieh, 1979]. This method was briefly used during the 1970s to locate mineshafts in the then West-Germany. The principle of the transmission method is that seismic waves propagating between the source and the receivers are affected by the mineshaft in between. In the case when there is no mineshaft present the seismic waves are unaffected. It should be mentioned that the wavelength is generally considerably larger than the size of the mineshaft and therefore the same seismic waves will be present in the data. However, the arrival time, the amplitudes and the frequencies of the various seismic events in the traces are affected by the mineshaft. By mapping these attributes for each trace, anomalies can be identified and located. Note that this methodology has been adopted at a much smaller scale of detecting voids in concrete using the impact echo method (Sansalone & Street, 1997).

The transmission surveys conducted in the mid-1970s consisted of one receiver which was located in a borehole and various shot points located in a semicircle around the shot point [Dresen et al., 1975, Dresen, 1977]. In this survey layout only body waves i.e. compressional (P-waves), shear (S-waves) and possible converted waves (PcS-waves or ScP-waves) can be analysed. Dresen and Hsieh [1979] showed that the transmission method can be adapted to avoid the use of destructive boreholes. The survey layout of this method consists of a one shot point with the receivers in a semi-circle around the shot point. In this case the trace attributes of the refracted P-waves, reflected P-waves Rayleigh waves are analysed.

7. Broadside shot gathers

The use of semi-circular survey grids is not practical at railways or roads, especially where embankments exist. The first reason is that only a small area can be surveyed. To survey a large area the receivers and the source have to be relocated. The relocation of the receivers is very time consuming. The second reason is that some receivers have to be located on the railway or road. This leads to the unwanted possession of track or road.

Therefore we proposed an alternative survey layout based on the broadside shot gathers [Telford et al., 1990]. In this layout the shot points are located on one side of the survey area and the receivers are located on the other side of the area (Figure 5). This layout slices the survey space horizontally. Since mineshafts are vertical structures the survey space cuts through the mineshaft. In conventional geophysical survey layouts where the sources are in line with the receivers the survey space is vertical and therefore numerous survey lines are required in order to locate the mineshaft. Furthermore broadside shot gathers do not require possession of the road or track. Another advantage is that by placing the sources and receivers parallel to the railway or road, topographical variations such as embankments and trenches have a minor effect on the recorded data. A disadvantage of the variable source-receiver distances in the broadside shot gathers is that various seismic waves will arrive at different times. Interference with other waves which have a different travel times curves will occur. This affects the attribute values of the traces.

8. Numerical modelling

In order to assess the potential of using the transmission method and the broadside shot gathers to locate mineshafts we developed a computer algorithm which simulates elastic waves propagating in a halfspace. The algorithm is based on a finite-difference time-domain scheme which provides a full wave solution to governing wave propagation equations. The modelled space is meshed using the rotated staggered grid. This experimental grid allows one to model strong heterogeneities such as air voids in mineshafts. In order to model a half-space, absorbing boundary conditions are required such that no reflections come into existence due to the truncations of the model edges. We developed a new type of absorbing boundary condition which is referred as the Recursive Integration Perfectly Matched Layer [Drossaert and Giannopoulos, 2007].

Various mineshaft models were simulated in which the size and shape of the mineshaft varied as well as various superficial deposits, thicknesses and various source frequencies. In this paper we present the model which closely resembles the mineshaft at the test site. A representation of this model can be found in Figure 6. This model consists of a mineshaft located in the middle of a 30m×30m×10m model. The void of the mineshaft is air filled until 1m depth from the surface. The mineshaft is backfilled till the surface. Due to weathering, agricultural usage and redevelopment the backfilling in the upper 0.5m has the same physical parameters as the superficial deposits. The superficial deposits-bedrock interface is located at a shallow depth of 1.5m. In Figure 6 the location of the source and the survey lines are indicated. Each survey line consists of 49 receivers. The receivers were located on the nodes of the model mesh and measure the vertical velocity of the displacement. The source consists of a force superimposed on the simulated stresses and its shape is Gaussian with a centre frequency of 25Hz.

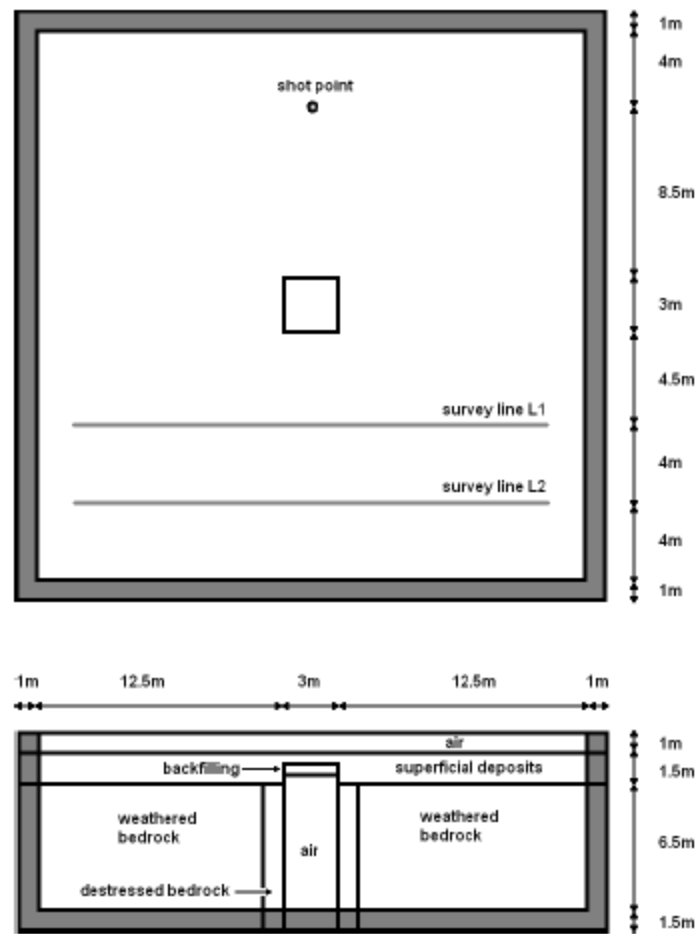


Fig. 6. Representation of the 3D model with the mineshaft outlined and the positions of the shot point and survey lines; top (plane view) and bottom (cross section)

8.1. Numerical results

The results of the simulations are presented as snapshots in Figure7. From the snapshots the following observations can be made.

- In the snapshot at 119ms, the wave front of the first seismic event is affected by the presence of the mineshaft. In other words the mineshaft causes delays in the first breaks.
- In the snapshot at 180ms, it can be observed that the amplitudes of the surface waves in the shadow zone of the mineshaft are increased.
- In the snapshot at 180ms, it also can be observed that the surface waves just off the shadow zone exhibit decreased amplitudes. The reason for the increase and decrease of amplitudes is associated with the widening and narrowing of the Fresnel zone.

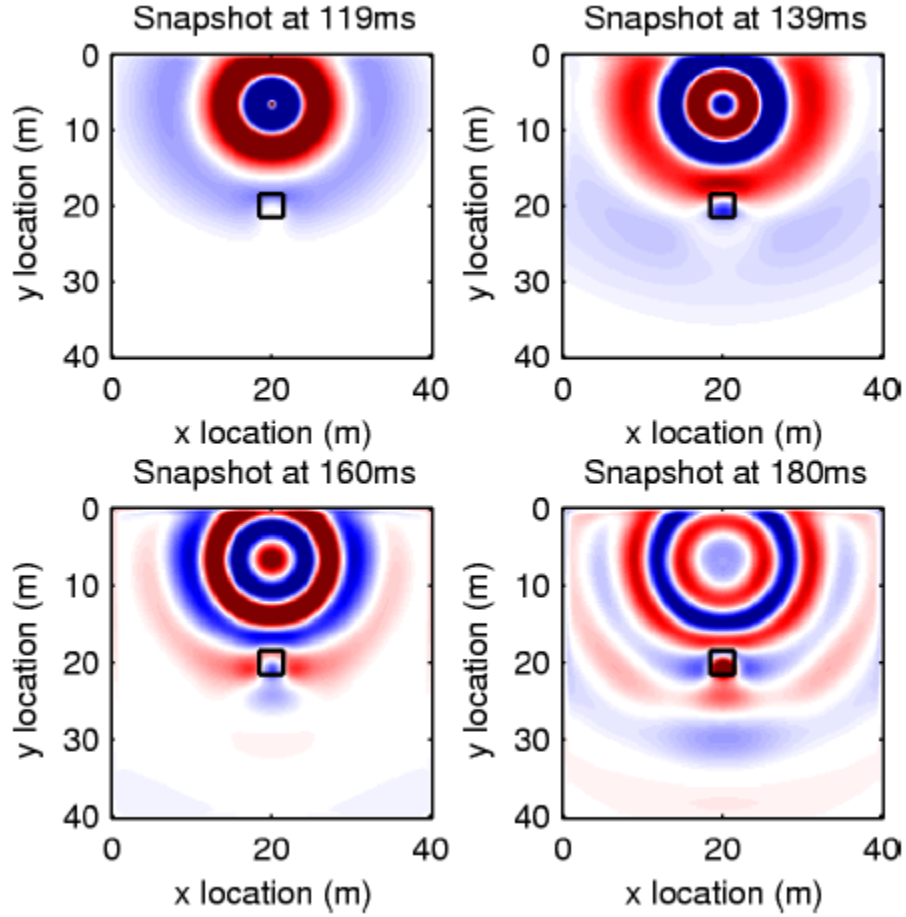


Fig. 7. Snapshots of the vertical velocity at the surface

8.2. First breaks

The first breaks i.e. the arrival time of the first arriving seismic event were determined by locating the amplitudes with a value that is -20dB of value of the first maximum. The results of the first break estimation can be found in Figure 8. For comparison reasons the first breaks of a reference model is also presented in this figure. The reference model does not contain a mineshaft. Other model and medium parameters are identical. Figure 8 shows that the arrival times of the first seismic waves are affected by the presence of the mineshaft. A delay can be observed at the receivers opposite to the mineshaft with the maximum delay at the receiver in line with the source location and the centre of the mineshaft. The delay is stronger at the survey line L1 than at survey line L2 which is located further away from the mineshaft.

The first break figures show that there is a good correlation between the anomalies and the location of the mineshaft. Therefore it can be concluded that by plotting the arrival times of the first arriving event, the location of the mineshaft can be determined.

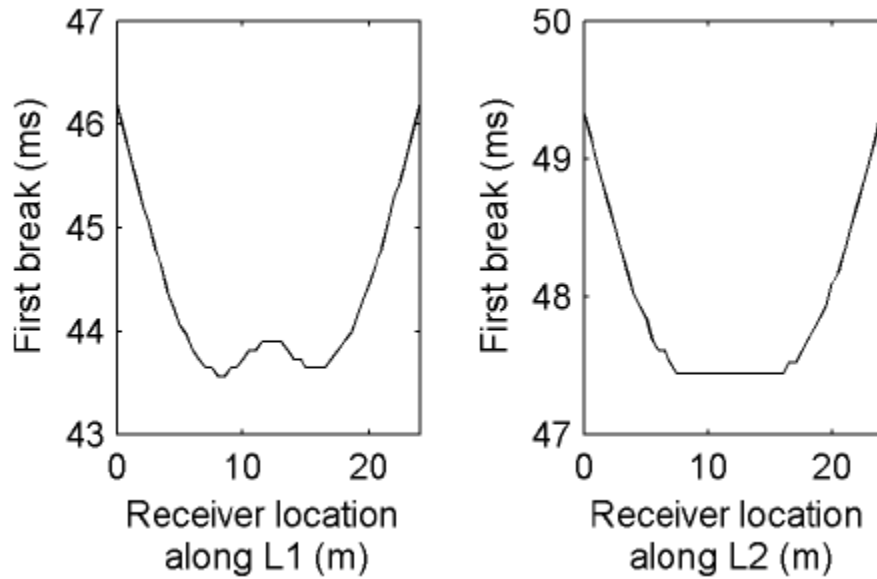


Fig. 8. Estimated first breaks at the geophones along survey line L1 and L2

9. Field experiment

In reality there is often a discrepancy between numerical data and field data. In order to assess the transmission method, pilot tests were conducted on a farmland in East Lothian. The test site consisted of a capped mineshaft with its location known. The mineshaft was rectangular shaped with dimensions of 2.5m by 3.5m. The depth of the mineshaft was 55m and it was filled with water till about 4m from the surface. The local geology is characterized by a very shallow weathered bedrock which shows a dip and cross dip along the survey lines. The superficial deposits consist of boulder clay.

The survey consisted of several shot point lines and receiver lines to simulate a survey as if the location of the mineshaft was not known. In this paper we only present some of the relevant shot gathers. The position of the shot point and the receivers is presented in Figure 9. The receiver spacing is selected to be 2m and the line spacing to be 4m. The receivers consisted of 4.5Hz geophones measuring the vertical velocity and the source consisted of a 14lb heavy sledgehammer and a metal base plate.

A trigger was connected to the hammer such that the seismic recorder, a DAQlink II, starts recording the incoming signal at the same moment that the hammer hits the metal plate. The survey was characterized by strong winds. The resulting data exhibit very low signal-to-noise ratio. The first breaks were picked by hand since automated picking cannot take into account the background noise. The results of the estimation of the first breaks can be found in Figure 10. The following observations can be made from these curves

- The first break curve of survey line L2 exhibits erratic behaviour which was caused by picking errors due to the low signal-to-noise ratio.
- Anomalous first break values can be observed at the receivers along survey line L1 opposite to the mineshaft at a distance of 20-24m.
- Similar anomalous values can be observed at the receivers along survey line L2.
- The delay caused by the mineshaft is of the order of 2ms.

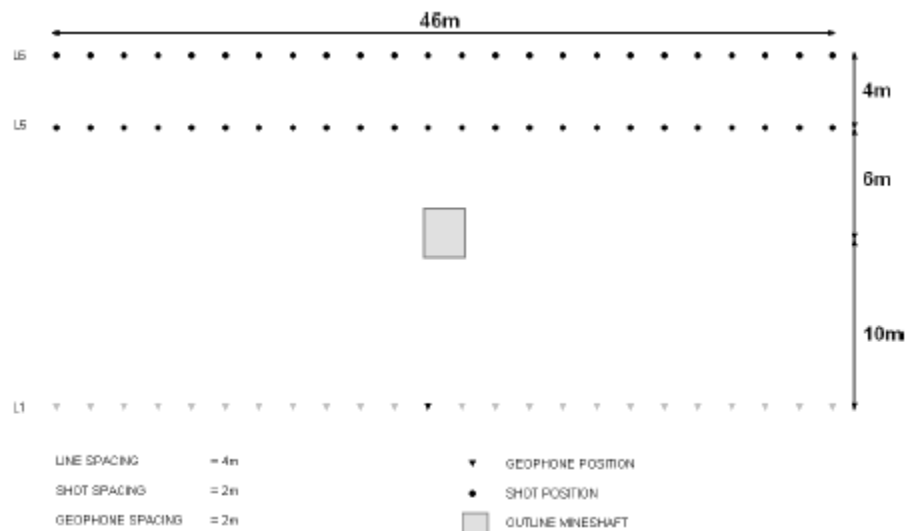


Fig. 9. Survey lay out

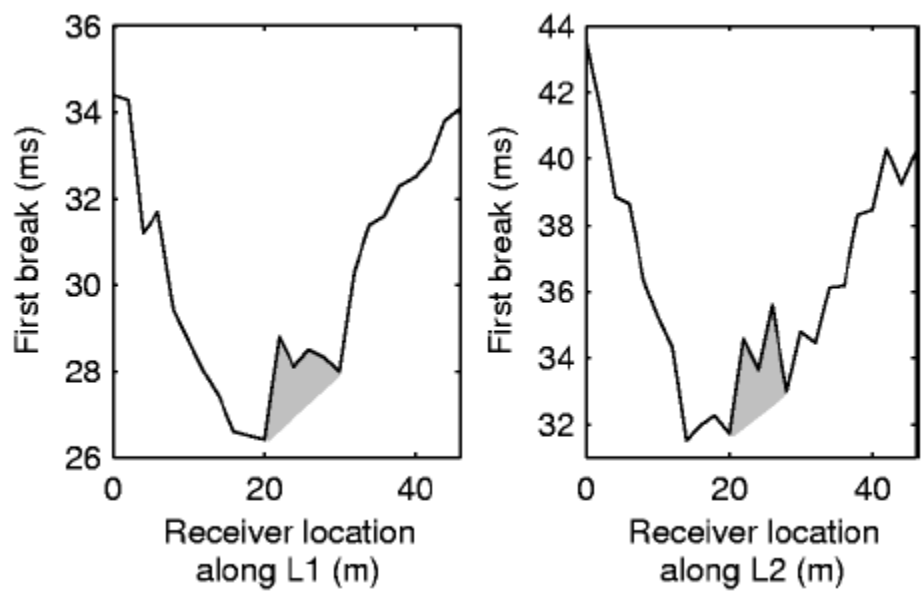


Fig. 10. First breaks of the experimental data

9.1. Practical considerations

A number of practical issues arose from the field experiment and from the more detailed numerical analysis given elsewhere [Drossaert, 2007]:

- Attempt to locate the survey lines as close as possible to the suspected location of the mineshaft. Anomalies appeared more focussed in the seismograms at survey lines closer to the mineshaft – and the location of the mineshaft could be determined more easily. Use high frequency sources. Waves containing high frequencies were more affected by the mineshaft than low frequency waves. Generating high frequency waves can be achieved by selecting different sources or by using high-pass filters, preferably before the analogue-digital conversion.
- In order to improve the signal-to-noise ratio heavy impact sources should be used such as a heavy drop weight source or accelerated hammer.

- It is easier to detect larger mineshafts. The larger the mineshaft the larger the anomaly. The models mineshafts of diameter less than 2m produced very small anomalies. However, it is very likely that using high frequency waves will resolve smaller mineshafts better. As a rule of thumb the diameter should not be smaller than a quarter of the wavelength (Diameter of mineshaft $> 2m$).
- A receiver spacing of approximately 1m is strongly recommended, especially when surveying for mineshafts of less than 2m. The same size of survey area is covered when using 48 receivers instead of 24.
- Receivers/Geophones must be calibrated.
- Ideally the bedrock should be deeper than 1.5m.

Although the seismograms of model 3 showed some anomalies related to the mineshaft, in practice random noise and shallow irregular bedrock interface and irregular surface would cause interference patterns which will complicate the interpretation of the seismograms.

10. Conclusions

The results of the research regarding the transmission methods using broadside shot gathers to locate buried mineshafts, was presented. The following conclusions were drawn:

- Using broadside shot gathers an area can be surveyed quickly and cost-effectively and does not require possession of railways or roads - which is particularly beneficial for transport arteries.
- The numerical models showed that the anomalous first breaks, amplitudes of the Rayleigh waves and dominant frequencies can be used to locate the mineshaft.
- The results of the numerical experiments and the field experiments showed that the transmission method using broadside shot gathers can be used to delineate mineshafts.
- The attribute curves of the first break successfully pinpointed the location of the mineshaft.
- The technique was less effective where a shallow superficial deposit overlays bedrock.
- A higher frequency source (greater than 25Hz) would be needed to identify mineshafts smaller than 2m in diameter.
- Signal to noise ratio could be improved by using calibrated geophones in conjunction with a higher energy source than a 14lb sledge hammer.
- A receiver spacing of approximately 1m is strongly recommended, especially when surveying for mineshafts of less than 2m.

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